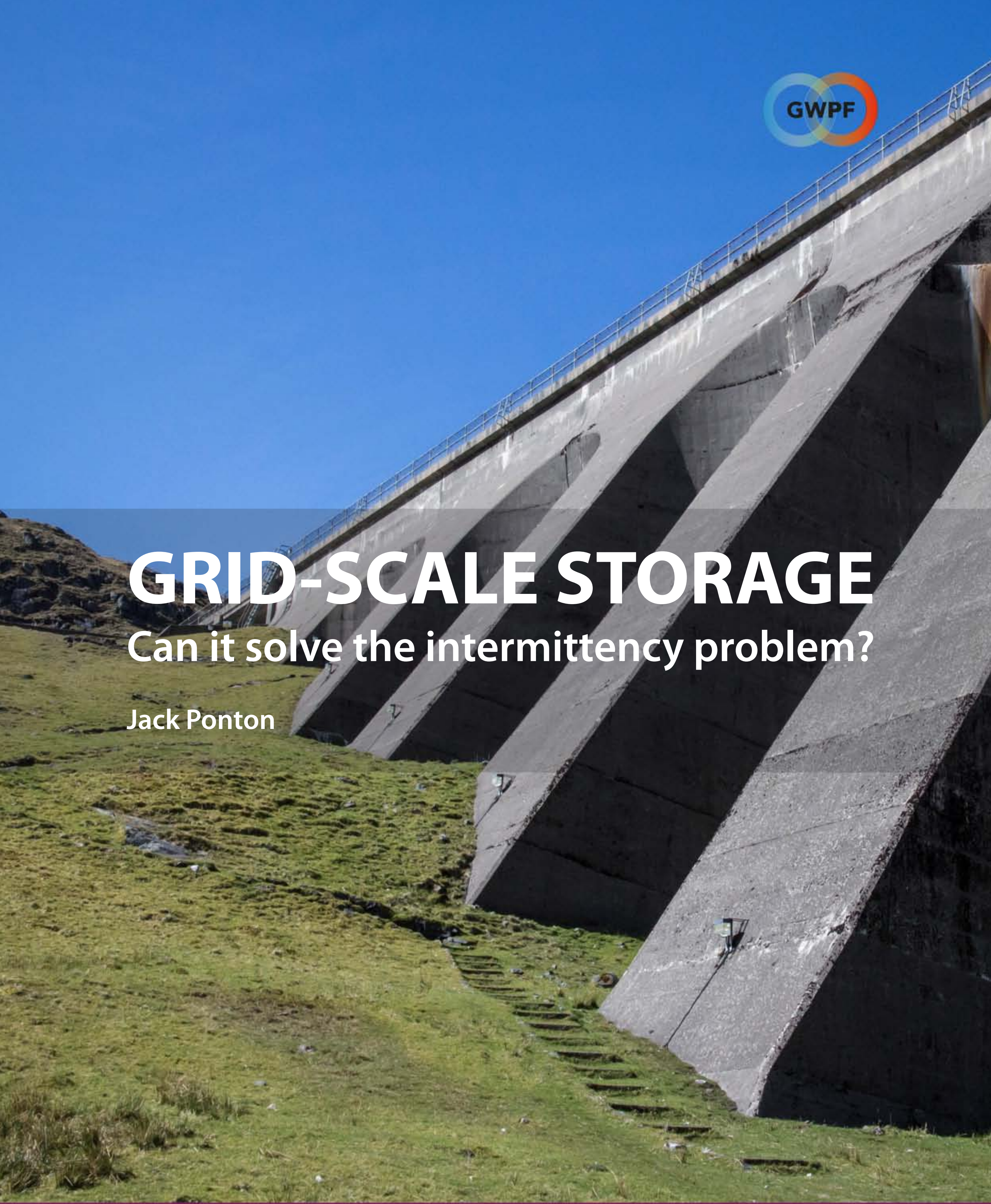

GRID-SCALE STORAGE

Can it solve the intermittency problem?

Jack Ponton

The Global Warming Policy Foundation

GWPF Briefing 39

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About the author

Jack Ponton is Emeritus Professor of Engineering at the University of Edinburgh, a fellow of the Royal Academy of Engineering and of the Institution of Chemical Engineers (of which he is a past vice-president).

His main research work was in mathematical modelling of complex engineering phenomena and software development. He has also worked in and with the chemical industry on a range of topics including health and safety issues.

A further research interest has been renewable and alternative energy: wave power, biofuels, hydrogen, ocean thermal energy and coal gasification with carbon capture.

His interest in wind power is more recent. As Professor Ponton explains:

> The reason for this is that nearly forty years ago, a colleague and I carried out some simple calculations about the potential for wind power in the UK. We concluded that useful amounts of energy could not be obtained without covering most of the country with wind turbines. At the time we assumed that no-one would consider doing anything quite so foolish.

1 Introduction

All but the most dedicated renewable energy enthusiasts now seem to understand that powering a modern society will require something else in addition to intermittent electricity generation. The currently fashionable 'something else' is storage. This paper will discuss storage technologies, Britain's current facilities and what might be needed to provide reliable power from wind, solar and tidal generation.

2 The purpose of storage

There are four reasons why storage is or might be provided on the grid.

Short-term storage can maintain grid stability by acting as rapid response capacity, for example in response to an unexpected increase in demand or loss of supply. The Dinorwig pumped storage scheme (see below) serves this purpose, as does a recently installed battery facility in Ireland. The requirements for this type of storage are easily met by existing technology and so will not be discussed.

Daily storage is intended to smooth out generation requirements between daytime demand which peaks around 6:30pm and low night-time demand between about midnight and 6:00am. Most UK pumped storage is of this sort. A similar requirement, but at different times, arises with solar generation, which of course disappears at night, although in Britain that is not the main problem with this technology, as will be seen.

Intraseasonal storage would be needed to even out the variation in intermittent forms of electricity generation, such as wind farms, the output of which can fall to near zero for several days at a time. There is no available storage technology that can deliver the capacity required, in the UK or indeed anywhere else.

Interseasonal storage that could store, say, surplus solar-generated electricity in the summer months for use in the dark northern winter, would obviously need a very large capacity. The technologies that could provide this facility economically are hardly developed.

3 Storage technologies

Electricity is not easy to store. In fact, it can only be stored in capacitors at an impractically low density. Even so-called 'supercapacitors' would be unsuitable for storage at the required scale. Practical storage thus requires that electricity be converted to either mechanical or chemical energy, with a consequent loss on conversion in each direction.

There are two measures required to define the performance of a storage system:

- the *power* it can deliver, typically measured in megawatts (MW)
- the amount of *energy* it can store, typically measured in megawatt hours (MWh).

The second measure is the more significant. The press often quote only the power figure, suggesting either a failure to understand or an intention to mislead.

Pumped hydro and other physical storage approaches

The most plausible form of mechanical energy storage, and the only one currently in use at grid scale, is pumped hydro. This is subject to significant geographical constraints, as it requires suitably placed high- and low-level reservoirs. Ecological considerations will normally mean that the high reservoir be fresh water, so the sea cannot be used as a lower source, further constraining possible sites.

No pumped storage has been built in Britain recently, but Scottish & Southern Electricity claim that their proposed 30-GWh Coire Glas development would cost £800m, or £27m/GWh. Cruachan, opened in 1965, cost £16m,[1] about £308m in 2018 money, and has a capacity of 10 GWh, suggesting a cost of about £30m/GWh today.

The turnaround efficiency of pumped storage is about 70%. This means that for every 1 GWh stored only 0.7 GWh is recovered. Compressed-air and liquid-air storage systems have been suggested, but would have lower efficiency than pumped hydro and would therefore probably not be feasible at scale. Schemes involving ballasted rail cars on sloped tracks or weights lowered down disused mine shafts are also unlikely to be scalable.

Batteries

Batteries store and release energy by means of electrochemical reactions. The best performing batteries today are based on reactions of lithium compounds. Lithium is the lightest metal and most electrochemically active. A lithium–air battery, similar in principle to the tiny zinc–air batteries used in hearing aids, could have an energy density comparable to fossil fuels, but unfortunately would not be rechargeable.

The most publicised large-scale battery is the Tesla Powerwall. The 14-kWh unit sells in the UK for £5,400, corresponding to £386m/GWh, more than an order of magnitude more than the cost of pumped storage. The largest battery installation to date is the 'world's largest battery' installed by Tesla in South Australia. The 0.129-GWh system is believed to have cost around US $38m, equivalent to £220m/GWh.

However, the storage capacity of this battery is insignificant on a grid scale. South Australia's typical demand for electricity is around 2 GW, which the battery could supply for less than four minutes. In fact, although press reports have suggested otherwise, its purpose is not to store surplus renewable energy but to provide stability on the local grid, which has been destabilized by an excessive proportion of wind power. Stabilization is in fact the purpose of nearly all larger grid-connected batteries.

Figures on the turnaround efficiency of battery storage are conspicuous by their absence. This will depend of a variety of factors, in particular charging and discharging rates. It is probably reasonable to assume between 80% and 90%.

The cost of battery storage is certain to fall, but the question is, by how much? Enthusiasts cite the order-of-magnitude reductions seen in solar panel costs. However, the technologies are not comparable. Silicon solar cells were a completely new technology when they appeared, whereas lithium batteries are a relatively mature technology. Moreover, batteries use a higher proportion of relatively expensive materials than solar cells.

The life of any battery will be much less than that of a hydro installation. Tesla offer a ten-year warranty on the Powerwall, its battery for domestic electricity storage, whereas the hydro station originally built for the aluminium works at Kinlochleven has been in operation since 1909.

Other forms of chemical storage

Finally, there is the idea of using electricity to make chemicals that are more easily stored. The most likely candidate is hydrogen, which can be produced relatively easily by electrolysis, a well-established process. It can then be used to generate electricity in a fuel cell. However, both of these processes have an efficiency of about 70%, so the turnaround efficiency is only about 50%.

Moreover, hydrogen is not easy to store. In volume terms – which is what matters for storage – it contains only about one third of the energy that natural gas does. Its low boiling point, −253°C, makes storage as a liquid difficult and expensive. Probably the only practical method of large-scale storage in the UK would be in underground caverns in salt strata. These caverns, largely a legacy from salt extraction for chlorine manufacture, are currently used mainly for natural gas storage. An estimate of the cost of hydrogen storage is given in Appendix A. The cost of the storage cavern alone, based on recent figures published for extension of the Aldbrough facility, is a surprisingly small £234,000/GWh. However, the total costs of the hydrogen approach to storage are dominated by the electrolyser and fuel cells, which at current prices might come to around £100m/GWh. The approach may therefore be cheaper than batteries but is several times as expensive as pumped hydro.

The idea that electrolytic hydrogen could be converted to other more easily stored chemicals such as methane or methanol is essentially a non-starter. The additional processing would add significant costs and would reduce the overall efficiency well below the 50% achievable with hydrogen. There would also be the need, if carbon dioxide emission reduction is the aim, for large-scale carbon capture, a technology which is still of questionable practicality, and which would introduce further costs.

4 Existing and possible future UK storage facilities

Pumped hydro

Britain currently has four pumped storage facilities: Dinorwig and Ffestiniog in Wales and Cruachan and Foyers in Scotland. Their total storage capacity is 27.6 GWh, so together they can only meet the average UK demand of 35 GW for about 46 minutes. At least three further developments are in planning in Scotland:

- Coire Glas with a capacity of 30 GWh
- 'Red John' near Loch Ness, with a capacity of 2.4 GWh
- Glenmuckloch, 1.7 GWh, based on an old opencast mine in Dumfries and Galloway.

A few smaller schemes have been proposed elsewhere in Scotland and Wales. The total capacity in planning is probably around another 36 GWh. Construction does not appear to have started on any of these.

In the 1970s a survey was carried out for a 72-GWh scheme at Craigroyston and Loch Lomond.[1] There were one or possibly two Welsh schemes, probably comparable in size to Dinorwig and Ffestiniog, so with a total of, say, 10 GWh. Total additional surveyed potential could be around 82 GWh. It seems unlikely that there are many further sites with significant potential in Britain.

In summary, total potential pumped storage capacity might be increased to a figure of around 225 GWh, representing about 6.4 hours of average demand.

It is important to understand why existing pumped storage was built and how it is used. Current storage was intended to complement nuclear generation and provide additional power at times of peak demand. Civilian power reactors in the UK are not designed to be turned up and down to meet changing demand; they can be shut down rapidly in an emergency but may then take several days to restart. In a system with significant nuclear generation running at constant output there will be a surplus of electricity overnight, or it will at least be available at a lower price. In pumped hydro systems, this cheap energy is used to pump water up to the upper reservoir, and this store of water can then be used to generate power at times of high demand and high prices. To make an expensive investment such as a pumped hydro scheme pay, it must be able to operate on a regular basis. It must be assured of both a regular supply of electricity at low cost and a guaranteed market to which energy can later be sold at a higher price. Current pumped storage operators are able to sell power at the evening peak every day throughout the year. As we will see, however, this would not be the case were pumped hydro to be used in conjunction with randomly intermittent wind generation.

Battery storage

A number of developers are installing battery storage facilities on electricity grids, but their purpose appears to be to provide short-term supply, typically for grid stabilisation or occasions when unexpected demand peaks or loss of generation send the spot price of electricity to ten or twenty times its usual value.

The only physical constraints on deployment of battery systems is the availability of the materials used. Lithium is plentiful, although expensive and energy-intensive to extract. Other metals, such as cobalt and nickel, could become constraining if large-scale battery construction were to take place worldwide.

At present, the main constraint to large-scale use of batteries is cost. As mentioned previously, while costs will certainly come down, they would have to do so by nearly a factor of ten to match pumped storage. However, if they did so, there would be no geographical constraint to their wider deployment. Based on a photograph of Tesla's South Australia installation, 1 GW of storage could probably be placed on a one-hectare field.

Hydrogen storage

There are no water electrolysis or fuel-cell installations in the UK above a few megawatts' capacity. As noted above, these are now established technologies and, although expensive, their wider use could bring down costs somewhat.

The main barrier to hydrogen storage is therefore likely to be the availability of suitable salt strata for caverns. The only existing facility for storing hydrogen in Britain is in a series of salt caverns on Teeside. The facility was developed by ICI and is now owned by Sabic. It can store up to one million standard cubic metres of hydrocarbon-derived hydrogen,[2] with a thermal value of 3.34 GWh, about one third of the capacity of the Cruachan pumped storage scheme.

The UK currently also has about 1200 million cubic metres of salt cavern capacity, currently used for storing natural gas.[3] There are also extensive unused salt deposits in England, mainly around Teeside and in Cheshire, although not all of these are suitable for gas storage as some contain fractures through which gas would leak. However, more importantly, we have recently lost the Rough facility, a depleted gas field that had been used since the 1980s for methane storage. Rough represented about two thirds of the UK's capacity, so its loss created a gas storage crisis. As a result, development of salt deposits for the foreseeable future will be for methane storage.

5 Matching storage to intermittent generation

There are three forms of 'renewable' intermittent generation currently operating or likely to be of significance in the UK: wind, solar and tidal stream. Each has different intermittency characteristics, which storage could attempt to alleviate.

Wind

Wind is the largest intermittent generator today. It is essentially random. Although the wind blows most strongly in the winter months of highest demand, it does so inconsistently and there can be periods of several days in which a high pressure system sits over northern Europe, bringing very low temperatures and essentially no wind at all. In summer, low-wind events of up to a week are common, and can lead to wind generation remaining between 3 and 10% of capacity.

Based on actual wind and demand data for February 2013, Andrews has run a series of simulations as to how wind generation supplying an average of 25 GW to the grid might be smoothed by the use of storage.[4] There are two ways of smoothing. One is to have the minimum amount of installed wind power to meet the average demand, and to have enough storage to smooth this out (Figure 1). The other is to increase the installed capacity, accepting that it will sometimes need to be curtailed, in order to reduce the storage requirement. The extreme of the latter approach would involve installing enough nameplate wind capacity to maintain supply at the minimum ever load factor with no storage. An economic optimum would occur between these two scenarios depending on the relative cost of turbines and storage.

Andrews shows that a minimum installed wind capacity of about 100 GW would be required. Under the most favourable circumstances, starting with full storage at the beginning of the month, 3100 GWh of storage would be required, and storage would end up only 10% full at the end of the month, posing problems if the next month did not start off windy.

To put these figures in context, the approach would need more than five times current installed wind capacity (19 GW, end of 2017) and nearly fourteen times our likely feasible pumped storage capacity (225 GWh estimate above). Even if such storage could be found, at £30m/GW it would cost about £90 billion. The additional 80 GW of turbines would cost, at about £1m/MW if onshore, another £80 billion. The total of £170 billion could buy eight 3.2-GW Hinkleys, capable of delivering rather more power 24 hours a day, 365 days a year.

Using the alternative strategy of more turbines and less storage, a possibly just feasible figure of 700 GWh of storage would require 200 GW of turbines. This combination would be even more expensive. Moreover, 1 GW of turbines occupies around 100 km^2, so 200 GW would occupy 20,000 km^2, about one quarter of the entire land area of Scotland.

Note that these calculations do not assume an all-wind scenario. An average of 10 GW baseload power is also required. This would have to be coal, gas, nuclear or biomass with an installed capacity of more than 25 GW. The calculations also assume 100% round-trip efficiency for storage rather than the 70% or so achievable with pumped hydro. The figures produced are therefore too optimistic.

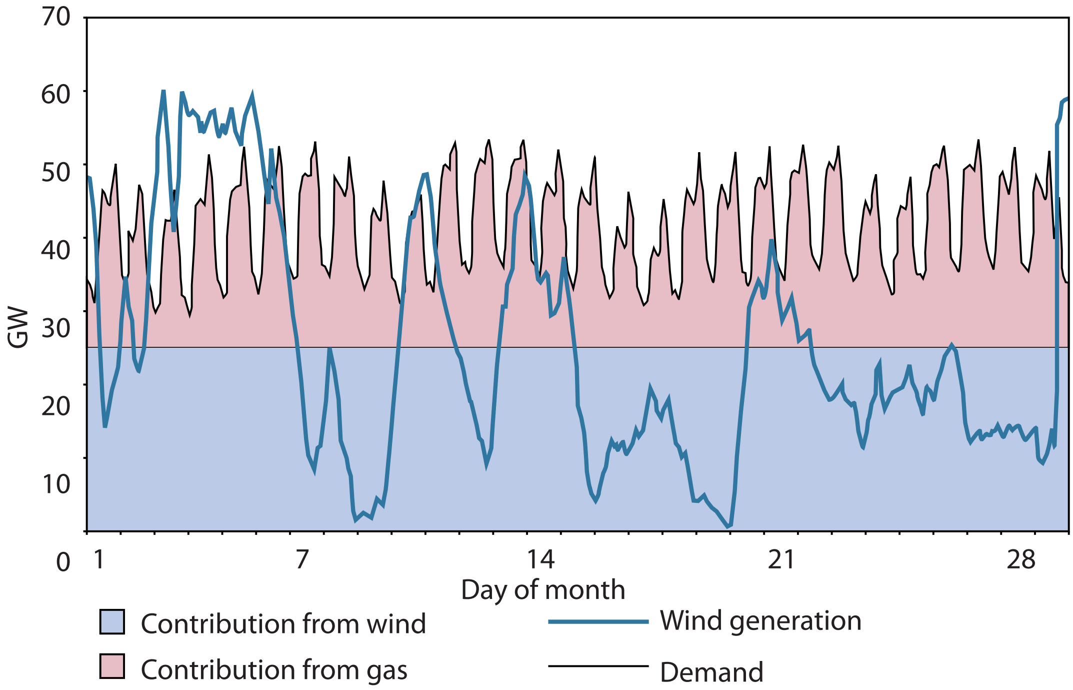

Figure 1: February 2013 wind generation scaled to 25 GW mean against actual demand.
Source: *Energy Matters*.[5]

The business model adopted in current proposals for pumped storage is something of a puzzle. It is unlikely to be the same as that currently used (see p. 3). The spread between overnight and peak prices is not normally very large, but is enough for operators with fully amortised plant to make a profit. However, it is insufficient to justify a new and expensive pumped hydro development. Nor does a new model predicated on buying cheap wind power at times of surplus and selling at a higher price during wind lulls seem plausible. As can be seen from the graph above, both peaks and lulls can last for several days. Thus, unlike the regular 24-hour fill-and-empty of the current operators' model, capital equipment driven by wind power could sit idle for a week or more.

Solar

In the tropics, at 20° north of the equator, a solar photovoltaic (PV) installation would expect to have an annual load factor of around 21%, a maximum of 25% and a minimum of 18%.[6] That is, over the year, a 1-MW system would generate an average of 210 kW. Its maximum generation averaged over one day would be 250 kW and its worst daily average 180 kW. A battery with 5.88 MWh capacity would be enough to store the maximum daily output and provide 24-hour power. Even minimum output would be useful; wind turbines in southern Europe can have load factors of less than 18%. At the cost of the South Australia battery, $295,000/MWh, this amount of battery storage would cost $1.73M. This is comparable with the present cost of 1 MW of PV. At these prices, for what is now effectively dispatchable power, the claim that solar would be cheaper than gas or nuclear might indeed (in the tropics) be true.

So in the tropics, solar plus storage does make good sense. And could also do so even just outside the tropics, say in Florida, at around 27°N, where minimum load factors are around 13%. Alas, Britain is nowhere near the tropics. In Aberdeen, 57°N, perhaps surprisingly one of the sunnier places in the UK, the predicted average load factor is only 11.7%, less than the worst in Florida. In fact, this figure is still very optimistic; actual recorded load factors range from 8.1% to 9.6%.

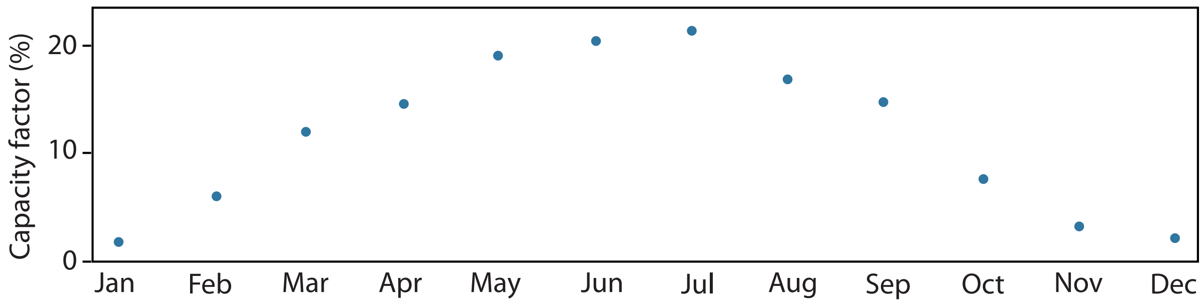

Figure 2: Solar capacity factors for Aberdeen, Scotland.
Source: www.renewables.ninja.

But this is not the real problem. In January load factors plunge to 1.76%, meaning that a 4-kW rooftop installation produces an average of only 70W and would generate only about 1.7 kWh over the day. This would be unlikely to meet daytime needs, let alone provide anything to store for use after the sun has set at around 3:30pm.

Would it be possible to store the summer surplus for several months for use in the winter? For a 1-GW solar installation, about 400 GWh of storage would be required to level the output to 110 MW. This greatly exceeds the entire UK pumped storage capacity. At current prices for battery storage it would cost an impractical £88 billion.

However, as shown above, the cost of the storage element for hydrogen is (relatively) modest, and with storage and discharge taking place over months rather than days, fewer electrolysers and fuel cells would be required. Since it is these elements that dominate the costing for the five-day lull wind scenario above, the cost of the system would be much reduced. However, because of the low turnaround efficiency of electrolysis plus fuel cells, the effective load factor of such a system would probably be as low as 8.5%. The calculations for a 1-GW installation, producing an annual average of 85 MW, are shown in Appendix 2. A minimum estimate of the cost, since installation and ancillary equipment costs for the electrolyser and fuel cells are not included, comes to £13.05m/MW, so the actual cost per megawatt would most likely be at least three times that of the Hinkley nuclear power station (£6m/MW).

However, the real problem would be providing the gas storage. A total of 90 million standard cubic metres would be needed, representing more than 6% of the UK's remaining gas storage capacity following the closure of Rough. This could hardly be justified for a mere 85 MW of generation capacity.

Tidal stream

Of the marine renewables technologies – wave, tidal lagoon or barrage, and tidal stream – only the last looks like a serious contender. Despite much taxpayers' money spent on their support, UK wave power companies have had a high death rate. Several tidal barrage projects have been proposed for the Severn estuary but abandoned. The latest scheme for Swansea Bay has sensibly been rejected by the Government despite lobbying by local interested parties. However, a number of 1.5 MW tidal stream turbines have now been operating in the Pentland Firth, the most promising tidal stream location, for over a year.

Power from tides is both intermittent and seasonal. However, it is a more plausible source of reliable electricity than wind or solar power since it is at least predictable. The short-term variation of tidal flow, between high and low tide, is six hours compared with the half-day cycle of solar and the unpredictable windy days. The 'season' for tidal flows, between spring and neap tides, is seven days, compared with the summer-to-winter variation for solar. Finally, for the Pentland Firth at least, even the neap tide season could provide a sensible level of power, unlike solar in wintertime Britain.

Tidal stream velocity varies sinusoidally, and since power depends on the cube of velocity, a 1-GW turbine would deliver an average of 0.42 GW. To smooth the output over the high-low tide cycle would require a relatively modest 0.945 GWh of storage. The Pentland Firth may have the potential to provide about 3 GW of tidal power, which at 42% load factor would need 6.75 GWh of storage, well within the potential of pumped storage.

The 'seasonal' variation is, however, significant; because of the cubic dependence of power on velocity, this variation is by a factor of about five. The Pentland Firth may be the only available site where the neap season velocity is sufficient to generate useful continuous power. Only chemical storage would be suitable for covering the low-velocity periods and the amount required would be comparable to that required to cover low-wind periods, as discussed above. In other words, it would be equally impractical.

A cost estimate for tidal stream power has not been attempted as this is a relatively new technology, and costs and sizes of turbines are likely to change. It should be noted that possible sites in the UK tend to be remote from consumers and so grid-connection and upgrade costs would be significant.

6 Conclusions

1. There seems to be no possibility that any existing storage technology can handle the intermittency of wind generation and make it effectively dispatchable. There are not enough sites for pumped storage, batteries are likely to remain too expensive and both processing cost and availability of storage sites would rule out storage as hydrogen.

2. Solar plus battery storage is probably already cost-competitive for locations in or near the tropics, where year-round load factors are acceptable and so only overnight storage is required. In the UK, low winter load factors mean that essentially no useful generation takes place in December and January. Only storage as hydrogen could provide summer-to-winter storage, but cost and lack of suitable storage sites would rule out this approach.

3. The predictability and relatively short length of the tidal cycle make the combination of tidal stream generation and pumped storage worth consideration. However, the number of tidal sites with sufficient stream velocity to provide useful generation in the neap tide season may be limited. There are also questions about the reliability, maintainability and lifespan of turbines in a very hostile marine environment.

Appendix 1: Cost estimate for hydrogen storage backup for wind

This estimate takes a very simple approach to give an idea of the magnitude of costs and the relative cost of the different components.

- Basis: 1 GWh hydrogen storage, needing 5 days for charge and discharge.
- Storage cost: based on Aldbrough NG storage extension, £290m for 370 Mm^3, £0.78m/Mm^3.
- Hydrogen energy content: 1 GWh = 0.3Mm^3, storage cost = £234k/GWh.
- Electrolyser generation over 5 days 0.3/5 = 0.06 Mm^3/day.
- Hydrogen density 2 kg/24 m^3 implies 4998 kg/day.
- ITM power 100 kg/day, electrolyser costs £713k, so electrolyser cost = £35.6m.
- PEM fuel cell costs around $4.5k, £3.375k/kW.
- 1 GW over 5 days at 70% efficiency implies 5.83 MW
- Fuel cell cost = £19.68m.

These are the bare equipment costs and do not include site preparation, installation or ancillary equipment, which could easily double the cost. It might be reasonable to take a figure of £100m/GW stored.

Appendix 2: Hydrogen for seasonal storage

- Basis: 1 GW rated panels. Effective load factor 8.5%, so actual output 85 MW.
- Surplus March–September used to make hydrogen to storage. Fuel cells used to make up deficit October-February.
- Electricity surplus 440 GWh, electrolysis 70% efficient makes 300 GWh hydrogen, requiring 90Mm^3 storage.
- Battery storage is used to smooth output over 24 hours. This significantly reduces electrolyser costs as this would otherwise have to cope with peak output.
- Electrolyser 5140 kWh/day. ITM power 100kg/day unit has capacity of 6 MWh/day, £0.713m.
- Storage based on Aldbrough scaled to 90 Mm^3 cost £70m.
- 85 MW of fuel cells at £3.375m/MW cost £287m.
- Cost of solar panels in US now claimed to be $1/W, so 1 GW costs £750m.
- Total cost £1,109m for 85 MW, £13.05m/MW.

Again, these are basic equipment costs (apart from storage) and so the real total would be much higher.

Notes

1. *Glasgow Herald*, 11 January, 1971.
2. Global CCS Institute (2012) 'Underground hydrogen storage', in *Operating Flexibility of Power Plants With CCS* https://hub.globalccsinstitute.com/publications/operating-flexibility-power-plants-ccs/2-underground-hydrogen-storage.
3. Beutal, T and S Black (2004) 'Salt deposits and gas cavern storage in the UK with a case study of salt exploration from Cheshire', Solution Mining Research Institute; Fall 2004 Technical Meeting, Berlin.
4. Andrews, Roger (2015) http://euanmearns.com/estimating-storage-requirements-at-high-level s-of-wind-penetration/.
5. http://euanmearns.com/estimating-storage-requirements-at-high-levels-of-wind-penetration/
6. All solar load factors estimated by Imperial College tool at: https://www.renewables.ninja/.

About the Global Warming Policy Foundation

The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

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